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FIELD COMPACTION OF BITUMINOUS MIXES FOR AIRPORT PAVEMENTS.(U)

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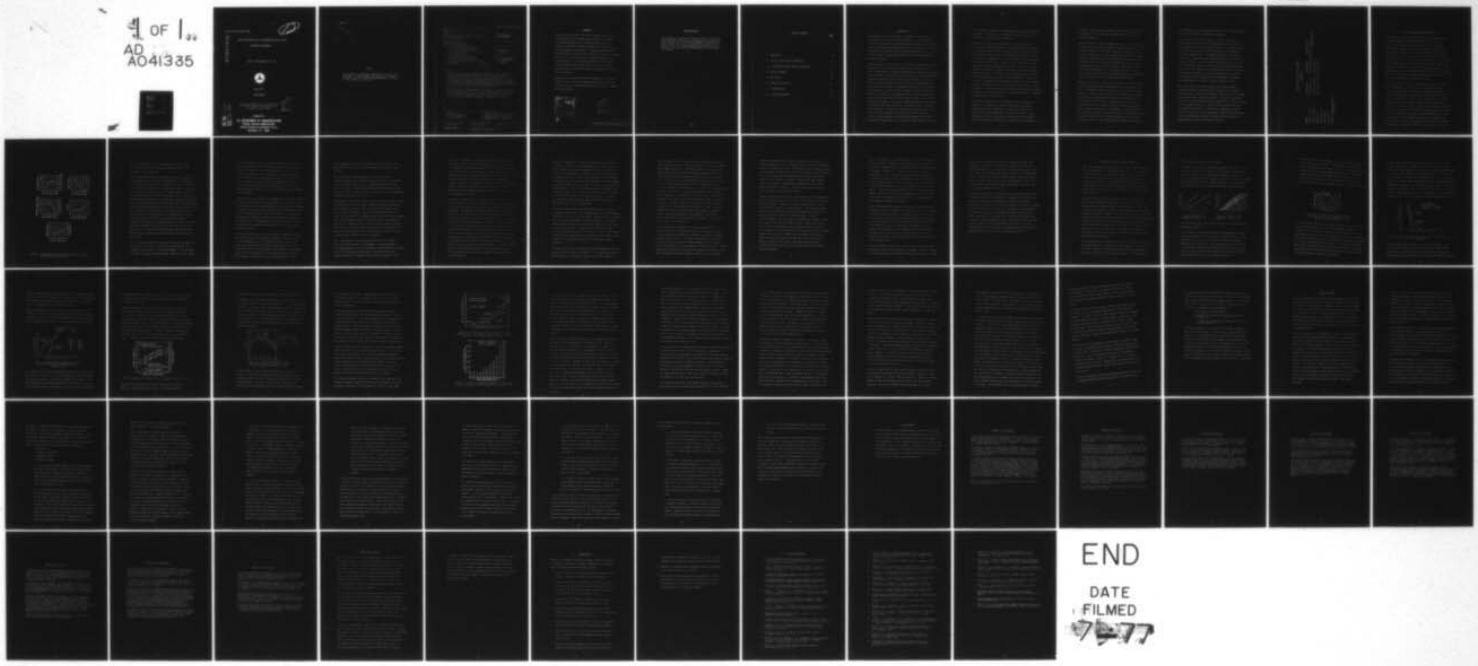

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FIELD COMPACTION OF BITUMINOUS MIXES FOR AIRPORT PAVEMENTS

Aston L. McLaughlin, Ph. D.

April 1977

Final Report

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16. Abstract

The report identifies the rationale for the Federal Aviation Administration requirement concerning the compaction of bituminous airport pavements (98 percent minimum of Marshall density) and outlines the mix design and construction factors directly affecting pavement compactibility. Information on the practices and problems associated with field compaction was gathered from interviews with cognizant field staff and notable experts, laboratory and field records of recently constructed airport pavements and from experimental and analytical research efforts by several agencies.

The findings are that the requirement is justifiable on the basis of expected pavement strength and durability; and that if certain design, construction and testing procedures are not within strict limits difficulty or failure to achieve adequate compaction will result. Recommendations are made that will assure and facilitate the attainment of high quality pavements.

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PREFACE

This study was undertaken in 1976 as an in-house effort by the Systems Research and Development Service (SRDS) of the Federal Aviation Administration (FAA) to explain the basis for the compaction requirements specified by the FAA for hot-mix, dense graded bituminous paving mixtures, to identify the factors which influence pavement compaction and to suggest procedures and practices which should be followed in order to facilitate compaction to required densities. The effort was requested by the Office of Airports Programs (AAP) to make changes, if necessary, in the advisory circular, Standards for Specifying Construction of Airports, AC No. 150/5370-10.

Preparation of the report was under the Supervision of Mr. Carl L. Schulten, Chief of the Airport Pavement Branch while Mr. Charles L. Blake was Chief of the Airport Division and Mr. David J. Sheftel was Service Director.

ACKNOWLEDGEMENTS

The cooperation of regional and district offices of the Federal Aviation Administration (FAA) in completing survey sheets, interviews with their staff and with the engineers at municipal and county airports was vital to the successful completion of this research effort. The Airports Engineering Division also gave invaluable assistance during the investigations and preparation of the report.

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I. INTRODUCTION

The general objective in the design of a bituminous concrete mix is to determine the cost effective type and gradation of aggregate particles which when coated with bitumen raised to high temperatures and compressed to form a skid resistant pavement will result in a product that is stable under pressure and durable against adverse environmental forces. How much of this objective is achieved depends almost entirely upon how well the mixture was compacted.

During the decade of the 40's, the U. S. Army Corps of Engineers, because of increasing activity in airfield construction, recognized the need to select a simple method of asphalt paving design and control that was rapid and reproducible while necessitating the use of light and portable testing equipment applicable for both laboratory and field usage. During this period, mix design parameters were selected by using the Hubbard-Field method which was unsuitable for determining optimum asphalt content and necessitated use of heavy and bulky equipment; the Texas Punching Shear method was too sensitive to aggregate gradation; the Hveem Stabilometer did not account adequately for mixture cohesion and was too sensitive to gradation and aggregate type; and the Skidmore Shear method needed expensive equipment that gave insufficiently reproducible values. Interest was then focused on the Marshall stability method which was still in its infancy but which promised to yield values for mixture properties similar to those obtained by the more recognized Hubbard-Field method. An important advantage was that it could also utilize apparatus that was

both portable and adaptable to existing California Bearing Ratio (CBR) equipment. The method was then adopted and developed by the Corps after much laboratory and field validation.[1]

The rapid growth of civil aviation in the 50's necessitated the construction of many new pavements but this growth was also accompanied by increases in aircraft payload, changes in gear configuration and use of small, high pressure tires which caused severe destruction of existing pavements. Pavement failures, such as rutting, shoving, channeling and fracture, caused by these changes had years before been observed on military airfields and resulted in efforts by the Corps to set new design and construction standards based on test track data and Marshall stability procedures.[2] The Federal Aviation Administration (FAA) which up to 1968 required that asphaltic concrete pavements be compacted to 92 percent of maximum theoretical density (8 percent air voids remaining) thereafter determined to raise this compaction requirement and to adopt the Marshall or Hveem method of preparing and compacting asphaltic mixtures as outlined by the American Society for Testing and Materials in standards designated ASTM 1559 and ASTM 1560.

Present FAA requirements[3] are that asphaltic concrete pavements be compacted to a minimum of 98 percent of the density of specimens compacted according to the Marshall procedure and that the mix as designed should have a maximum air void ratio of 5 percent. A mix designed and rolled to these specifications would yield a maximum in-place air void ratio of 7 percent and a minimum theoretical density of

93 percent. These requirements therefore represent an increase of one percentage point over previous compaction specifications for bituminous pavements.

While the increase in degree of compaction resulted out of necessity it has tended to remove airport bituminous pavement construction out of the technical capability of some small contractors accustomed to less rigorous criteria used for roadway construction; has required increases in energy consumption and labor; has necessitated greater selectivity of materials and has necessitated the utilization of better, more efficient and effective compaction equipment. However, these effects are largely being overcome by a wider understanding of the factors that influence the compactibility of bituminous pavements and by designing and rolling mixes to certain well defined specifications.

Experience has shown that compaction to 98 percent of Marshall density is possible only when some fourteen variables are simultaneously satisfied. The variables resulting from design, construction and testing practices are largely under the control of the engineer and contractor but those that are environmental in character, while they cannot be controlled, can be evaded. Thus compactibility of the mix can be assured by choices in its Marshall stability, workability, the type, shape, texture and gradation of the aggregates, type and proportion of the bitumen, the water content and stiffness of the supporting layers, the amount of mineral filler, the laydown temperature and, finally, the compactive effort. Windy conditions and low ambient temperatures,

both of which cause the hot mixture to cool before it can be effectively rolled, may be avoided by suitable job scheduling.

Investigations into reports of failure to attain the 98 percent of Marshall density on airport projects have revealed that in more than fifty percent of the cases the Marshall stability of the mixture was in excess of 2,500 lbs (11.1 kN) thereby offering too much resistance to the rollers commonly used. (The Marshall stability is the maximum force that a cylindrical specimen compacted and tested in a specified manner can resist.) In other cases, roller weights were insufficient or the temperature at which the mixture was laid (laydown temperature) was too low. Many instances have also been seen where late laboratory reports made it impossible to initiate remedial action and others where technicians were using faulty testing equipment and procedures that underestimated the degree of pavement compaction achieved.

Many state and municipal agencies engaged in setting standards for bituminous pavement construction require compaction to 97 percent of Marshall density. Additional densification under traffic over the pavement lane has however always been realized. On airport pavements and especially on runways minimal additional densification is desired because this has generally taken place along aircraft wheel paths which vary horizontally only slightly. On some airport pavements where densification from traffic occurred longitudinal channels have been observed and have caused drainage problems to develop with the possibility of hydroplaning along with some rutting and fracture.

MAJOR FACTORS AFFECTING PAVEMENT

COMPACTION

Design	Construction	Environmental	Quality Control
Subgrade Reaction	Compactive Effort	Ambient Temperature	Testing: Accuracy, Equipment, Staff
Marshall Stability	Laydown Temperature	Base Temperature	
Workability	Water Content of Base	Wind Conditions	
Asphalt Content			
Mat Thickness			
Asphalt Type			
Aggregate: Gradation, Texture Shape, Type			

II. DESIGN FACTORS AFFECTING COMPACTION

The performance of bituminous pavements is not only dependent upon how well the mixture was compacted, tire pressure and number of repetition of loadings, and climatic factors but also upon the characteristics and proportions of the constituents. For airport pavements lean mixes with good mechanical interlocks are required to resist traffic. The objective of mix design is to produce a workable mixture that has both stability under load and durability in service by making suitable choices in the amount, type and grade of bitumen, the shape, size, absorptiveness, gradation and physical properties of the aggregates and in the percentage of air voids to remain after compaction. While all of these factors determine eventual pavement performance some of them influence mixture compactibility as well.

Many cases have been reported in which failure to achieve the minimum field requirement was corrected by merely increasing the asphalt content without redesign of the entire mix. While this practice can reduce the mix stability to a degree where the mixture is more pliant under the weight of the roller for greater compaction it also reduces the design air voids by partially filling them with bitumen. When compaction to 98 percent or more of Marshall density then occurs there may be insufficient air voids to accomodate the excess bitumen and flushing will result. Pavements were seen at some airports where slick, tacky surfaces were in evidence during hot weather and along wheel paths. Cutting back on the amount of bitumen may also reduce the mix stability for greater ease of compaction but without redesigning the entire mix

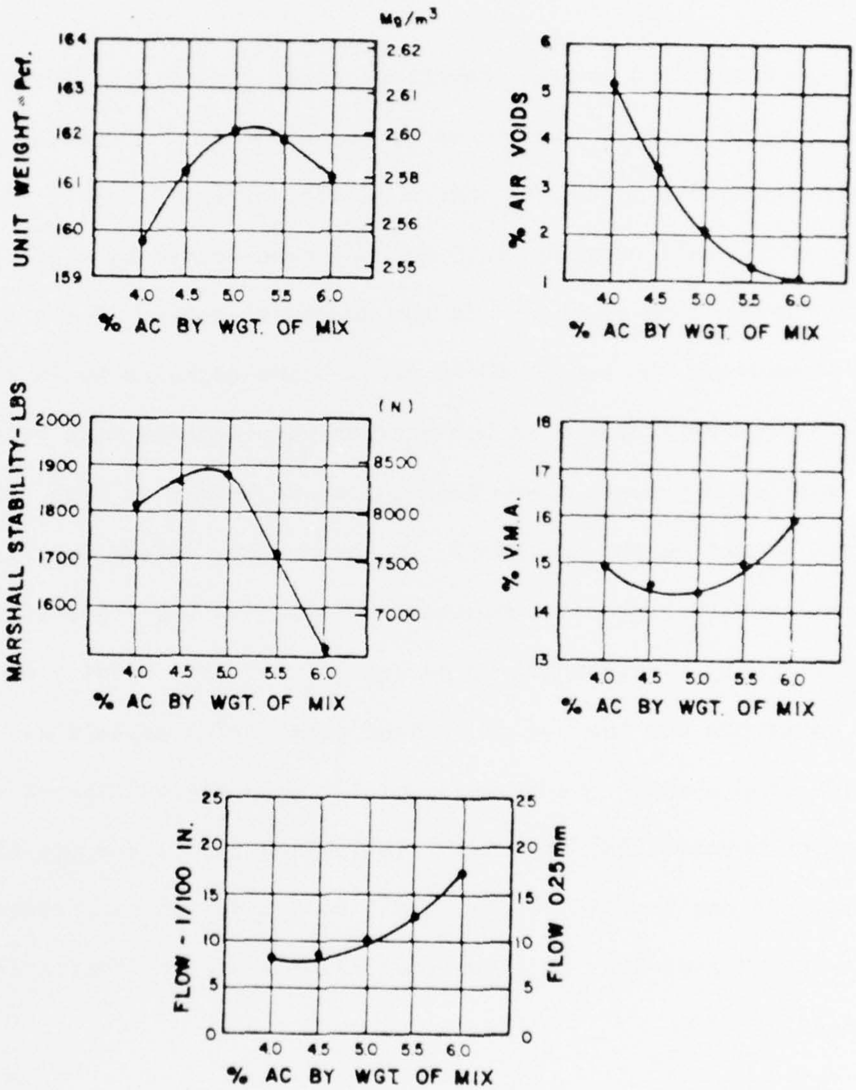

FIGURE 2-1 Test property curves for hot-mix design data by the Marshall method (After Ref. 4)

this is equally undesirable since reference to Figure 2-1 shows that the air voids ratio will increase; complete coating of the aggregates is also jeopardized.

Current specifications require penetrations of 85/100 and 120/150 for asphalts used in airport bituminous paving projects. (Penetration is the distance in millimeters that a needle, as specified in ASTM-D5, at 77°F or 25°C will progress in 5 seconds when loaded by a 100 g load.) The belief among some engineers in the southwest region of the U.S.A. is that permitting the use of 60/70 penetration asphalts would lead to better pavement performance in hot weather when temperatures become very high. Existing pavements there tend to become tender at high temperatures during the summer months and could, in their view, suffer further traffic densification with probable flushing. This region has reported very little difficulty in attaining 98 percent of Marshall density on its airport pavements but the use of a lower penetration asphalt as suggested could change this if maximum allowable viscosities at rolling temperatures between 250°F and 275°F (121°C and 135°C) are not also specified. It has been found that mixes designed with high viscosity asphalts are as resistant to compaction as they are to densification under traffic.

Also, in this region, many localities that are quite hot in summer are cold in winter too. There is a critical low temperature at which transverse cracks develop in a bituminous pavement. It has been shown by studies[5] in Canada that high penetration asphalts, such as 120/150,

on test pavements developed very little transverse cracking while the lower penetration ones, 85/100, under the same conditions developed significant cracking. A still lower penetration of 60/70 could be expected to perform even less satisfactorily. Although temperatures in the Southwest would not be likely to drop as low as at the test site in Canada, it is still reasonable to assume that the lower penetration asphalt would perform less satisfactorily than the two higher penetration grades for the seasonal low temperatures experienced in the Southwest.

Studies show that the frequency of low temperature cracking varies directly with the age of the asphalt concrete pavement as well as to the length of time during which the pavement remains in a cold condition. Pavements on a subgrade of sand were also observed to be more susceptible to this type of cracking than those on clay and the research also showed that thin pavements crack more frequently from sustained low temperatures than thicker ones. A mathematical model has been developed to predict the frequency of low-temperature cracking when the values for these variables are known.[6]

Much research has been done to relate the shape of aggregate particles with the characteristics of bituminous pavements. It has been shown that flaky aggregates used in the asphaltic concrete mix give rise to low compactibility and stratification under compaction.[7,8] The studies also show that when 30 percent of all particles in the mixture have an aspect ratio exceeding 3.0 the Marshall stability, isotropy and resistance to horizontal forces are adversely affected. This

type of aggregate also has a high breakage value and, because of its high specific area, requires much more bitumen for coating than rounded types.

The ASTM D693-71A[9] recommended practice is that the portion of aggregates retained on a 3/8 inch (9.5 mm) sieve should not contain more than 15 percent by weight of flat or elongated particles with aspect ratio of 5 or more. Current FAA specifications allow a maximum of only 8 percent to have an aspect ratio of 5, but set no limit on the percentage of particles with aspect ratio of 3.0.

Flat aggregates in the mixture tend to assume a horizontal position during compaction with a roller but assume a random orientation when compacted under laboratory conditions. Here, the incidence of breakage is also greater than on the pavement. A fair comparison between pavement core density and the density of a specimen compacted using the Marshall procedure cannot be made unless the particle orientations in the two samples are nearly equal. However, failure to attain the minimum compaction requirement on airport projects has never been attributable to the shape of the particles; probably because other resistrictions are placed on the type of rocks that are crushed to produce the aggregate.

Other considerations in the mix design evaluation are the hardness, porosity and absorptiveness of the aggregate. The minimum hardness of the coarse aggregate to be used in bituminous concrete pavements is covered in the FAA specifications and is based on test procedures for wear outlined in AASHTO T96. Aggregates might however be resistant to wear

but still be absorptive to the bituminous cement in varying degrees. The amount of asphalt absorption, expressed as a percentage by weight of the aggregate, is readily determinable[4] but specifications should also dictate limits of absorptiveness. Too great a capacity for absorption may lead to pavement failure because the thickness of the binder proper between particles is reduced and a deterioration of physical properties of the aggregate in the zone of absorption becomes evident. The results might then be loss of stability, a general inability to resist weathering from water action and little resistance to low temperature cracking.[10]

Pavements with highly absorptive aggregates were observed in some areas and, while they are still too new to show signs of disintegration, seem to have the same appearance as much older pavements with normal aggregates. Underestimation of aggregate absorptiveness gave rise to a mixture that with time became too lean but overestimation would have been equally undersirable because the excess bitumen that was not absorbed would yield a slick, unstable pavement. The effect of absorptiveness on total voids and bitumen content in mix design has been studied[11] and efforts to evaluate specific gravities more precisely have led the FAA, the Corps of Engineers and the Asphalt Institute to adopt the bulk impregnated specific gravity method in design of paving mixtures. It is suggested that specifications be written to outline limits of acceptability concerning absorptiveness and permeability. The specifications must of course be defined for ranges of asphalt penetration index since aggregates tend to absorb more asphalt of high penetration than of low penetration.

Gradation of aggregates, i.e. grain size distribution of particles in the blend, is required by all specifications to lie between certain limits designed to assure near maximum density of the collection of particles. When aggregates are graded to satisfy the Fuller equation for maximum densities, a workable mix and minimum voids are attained. A modification of this equation has been adopted by the Federal Highway Administration (FHWA) and is called the 0.45 power curve which many mix designers prefer. Limits set by FAA for gradation of aggregates, when compared with these sets of curves, yield a coarser mix in the large sieve sizes and even more so in the finer sieve sizes. The result is less workability (harsh mixes) and lower densitites than is possible with limits closer to the 0.45 power line.

In many cases where minimum compaction requirement was not attained the aggregate gradation had to be changed to allow for more precentages passing the no. 40 to no. 200 sieve sizes. These, referred to as carrier sizes, are preferably obtained from natural deposits. In some other instances paving technologists have found that mixes that contain more than 30 percent of the no. 30 sieve size are difficult to compact because the rounded particles of this size roll in front of the rollers. A suggestion has been made that the FAA limits should be lowered for the finer sizes to facilitate greater ease in attaining high pavement densities.

The source of difficulty most often encountered when pavements are to be compacted is the harshness of the mixture. This harshness has been due almost entirely to the practice of manufacturing coarse aggregates

(those retained on the no. 8 sieve size) by crushing large rock masses thereby producing fractured faces and sharp edges. This type of geometry causes immense resistance to compaction, produces very high stability mixes and, while the FAA advisories suggest the minimum amount of such coarse particles for use in making the mix, no upper limit has been set. Also, in previous years the minimum amount of crushed material retained on a no. 4 sieve was required by the FAA to be 60 percent by weight. Currently, the amount for retention by a no. 8 sieve size has been increased to 90 percent by weight. Studies by the Ohio Department of Highways and the University of California[12,13] show that angular coarse and fine aggregates in the mixture gave very high stability values and required more roller coverages to compact than when these particles had fewer fractured faces. In many cases the mix design for airport bituminous pavements has had to be adjusted by including a higher percentage of asphalt, reducing the angularity of the aggregate, increasing the natural sand content, using a softer grade of asphalt or reducing the filler content of the mixture.[14]

An investigation was conducted by the Corps of Engineers[15, 2] to evaluate the effects of high pressure tires, such as those used in aircrafts, on pavement performance and to update, if necessary, bituminous pavement design criteria. It was found that pavements constructed on high quality bases gave equal performance whether they were designed with uncrushed gravel for coarse aggregate or crushed limestone for coarse aggregate, provided that all other design criteria were satisfied. Pavements designed from mixes with Marshall stabilities near the minimum

required by the FAA have been found, according to field reports, to be readily compactible and have not shown any signs of distress under aircraft traffic or environmental forces. (The minimum Marshall stability required by FAA standards is 1,800 lbs. or 8.0 kN for air carrier airports and 1,000 lbs. or 4.4 kN for general aviation airports.) Marshall stabilities higher than these levels and produced by requiring too high a minimum percentage by weight of aggregates with fractured faces have caused needless additional resistance to compaction and have also led, in a structural sense, to overdesigned pavements.

Reports received from paving project staff indicate that mix designs with Marshall stabilities in excess of 2,400 lbs (1o.6 kN) are the rule rather than the exception. (There is at present no maximum limit set by the FAA on Marshall stability of bituminous mixes.) Some laboratory reports have been seen where mixes were designed with Marshall stabilities of close to 4,000 lbs (18.0 kN) for airport pavements. Naturally, effective compaction was never possible even with heavy vibratory rollers. It is apparent that some mix designers prepare formulas without regard to the capacity of the equipment that is going to compact the mixtures on the pavement. From the standpoint of strength and durability a pavement compacted to 98 percent of Marshall density and made from a mix with Marshall stability at 1,800 lbs (8.0 kN) and 5.0 percent air voids is expected to perform better than one made from a mix with Marshall stability of 3,600 lbs (16.0 kN) and 5.0 percent air voids but which cannot be compacted.

Present requirement for the maximum amount of air voids in the design mix is 5.0 percent. Assuming that the pavement will be compacted to 98 percent of Marshall density the in-place air voids will amount to about 7.0 percent. The experience of the Corps of Engineers and other organizations is that as in-place air void percentage increases above 7.0 percent the pavement becomes increasingly permeable and leaks water to the underlying layers. The view is, also, that when the percentage is 10.0 percent the expected life of the pavement is reduced by fifty percent. A pavement that was compacted to only 95 percent of Marshall density (reports with less than this compaction have been seen) would on this basis deteriorate twice as fast as if it had been compacted to the minimum requirement of 98 percent.

Asphalt technologists have shown that an increase in the percentage of in-place air voids is accompained by an increase in the rate of oxidation, age hardening and embrittlement of the asphalt concrete. A great deal of research work has been done on the embrittlement and aging process in asphalt pavements and some fifteen possible causes are suggested.[16] While volatization, surface photooxidation, photochemical action, polymerization, exudation of oil and changes by nuclear energy cannot be avoided, the major causes due to ingress of air and water can be eliminated by leaving as little in-place air void percentage as possible in the finished product.

An excessive amount of air voids (8.0 percent by most authorities) has, in addition, a direct structural effect. The greater the number of voids the lesser the net cross sectional area becomes and this results in lower

tensile and shear strengths than would be attainable with lower void percentages. The access of air and water progressively reduces the cementing character of the asphalt which, becoming hard and brittle with time, lowers the structural capacity and resilience of the pavement even further. Failure of the asphalt concrete composite construction ensues under the action of applied wheel loads and environmental forces. The use of asphalts with a high penetration index has met with some success in retarding pavement embrittlement.[17]

It should be noted, finally, that apart from the Marshall method of mix design the resistance to deformation by a compacted specimen may also be measured by using the Hveem stabilometer, unconfined compression, Hubbard-Field or triaxial test and that the maximum load obtainable depends on the kind of test that is used. Also, information concerning physical characteristics such as friction angle and cohesion can only be made with any certainty by the triaxial test. While some studies have shown correlation between strength and Marshall stability,[18] friction angle and Marshall flow,[19] some paving technologists still believe that triaxial tests should be used for purposes of analyzing these mixes and that the Marshall method be used as a tool for design and control.[20, 21]

III. CONSTRUCTION FACTORS AFFECTING COMPACTION

Many airport engineers believe that the most difficult and certainly the most troublesome phase of a bituminous pavement project is in the actual preparation and rolling of the mixture. Factors vital to successful compaction are encountered at this time and while their degrees of influence are the subject of many research efforts they still remain largely empirical. Two of the factors that underlie most compaction problems during construction are the temperature of the mixture and the rolling technique.

Experience in the industry has shown that very little compaction is possible after the pavement cools below 175°F (79°C).[22] How soon the mat reaches this temperature depends on its thickness, the laydown temperature, the temperature of the base, ambient temperature, wind velocity and mixing temperature. Because of the fact that most pavement compaction takes place between 275°F and 175°F (135°C and 70°C), some experts question the validity of the Marshall stability test which requires the laboratory asphaltic mixture to be compacted at 250°F (121°C), or at some specified viscosity, and tested at 140°F (60°C). In spite of this apparrent inconsistency the test still provides a reference against which pavement compaction might be measured.

Studies sponsored by the Highway Research Board[23] have established relationships between amounts of temperature loss and elapsed time for various conditions. While these results were based on work with highway pavements they are equally valid for airport pavements. The figures shown

are reproductions of some of those findings.

In Figure 3-1 the number of minutes elapsing before a 2.0 inch (5.1 cm) mat cools to 175°F (79°C) is seen to be about 50 percent greater than for a 1.5 inch (3.8 cm) mat under similar conditions. Work done on New Jersey Highway pavements[24] indicates that there is a parabolic relationship between cooling time and pavement thickness. It should be noted that this same study also showed that there was an intensification of

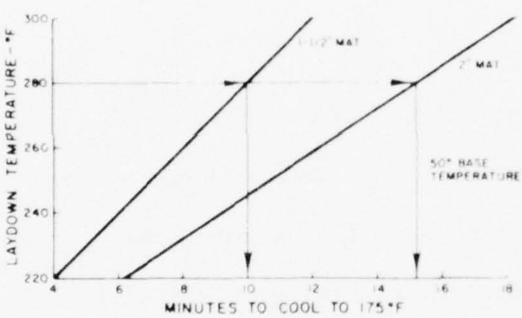

Figure 3-1. Effect of mat thickness, after Ref. 23

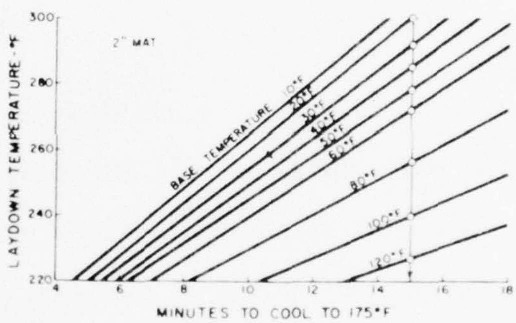

Figure 3-2. Effect of base temperature, after Ref. 25.

heat loss when rolling commenced since additional heat was drawn off by the rolling equipment.

It is reasonable to expect that higher laydown temperatures will give longer cooling times. This relationship is evident in Figure 3-2 which was drawn for a 2.0 inch (5.1 cm) thick mat. While high laydown temperatures will facilitate a longer rolling time before 175°F (79°C) is reached these temperatures create higher construction costs and, as will be pointed out later, higher temperatures than say 300°F (149°C) are not necessarily helpful in the compaction process.[22]

Transmission of heat to the subgrade is the most important factor that causes cooling of the hot mixture. The New Jersey studies[24] already referred to indicate that this source of heat loss is many times greater than the loss to air at ambient temperatures. Results of theoretical studies[26] also indicate that the heat flux into the base tends to be greater than into the air and therefore temperatures at the bottom of the mat are lower than those at the upper surface. The lines in Fiqure 3-3

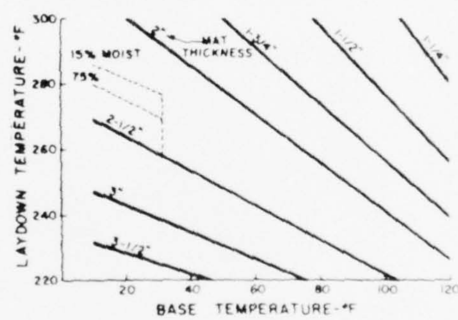

Figure 3-3. Illustration of suggested cessation requirements - 15 min. rolling time, various mat thicknesses, after Ref. 25.

from the National Asphalt Paving Association show how a contractor should vary the laydown temperature in order to allow himself 15 minutes of rolling time for any given mat thickness and base temperature. The base temperatures below 32°F (0°C) do not assume that a frozen condition exists. When the base and subgrade contain frozen moisture higher laydown temperatures are required and these would vary according to their moisture contents.[25] These figures show relationships that may be used for guidance only since environmental factors usually encountered during construction would change the laydown temperature requirements drastically.

An important factor determining the rate of loss of heat from the mat during construction is the wind velocity.[22] This has been the subject of many studies and Figure 3-4 is reproduced below from material published by the Association of Asphalt Paving Technologists.[26] It is clear, as one might expect, that the upper surface temperature is affected by wind velocity to a greater extent than the lower surface. On some airport paving projects, especially those located near coastal regions, high winds have caused such rapid cooling that a hard crust quickly develops at the upper surface of the mat and attempts to roll the pavement have invariably caused cracking of this crust and difficulty to attain adequate compaction. As

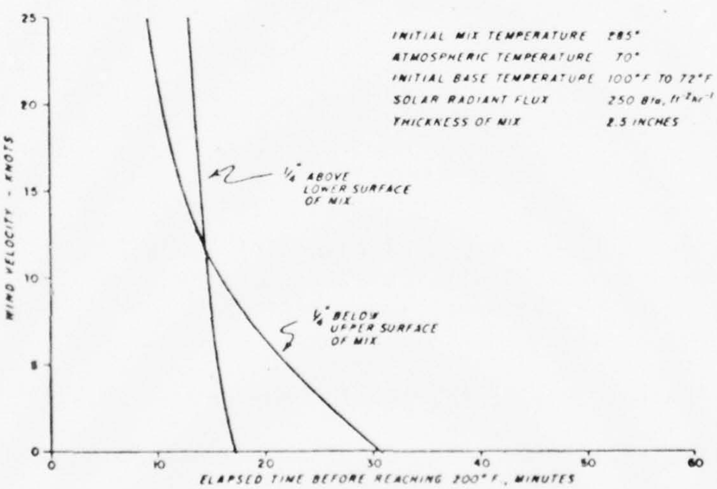

Fig. 3-4. Elapsed Time Before Reaching 200°F. vs. Wind Velocity, after Ref. 26

shown in Figure 3-4 the upper surface would take 31 minutes to cool to 200°F (93.3°C) under a no-wind condition versus 9 minutes under a wind velocity of 25 knots. With an unvarying rolling technique and laydown temperature a mat might easily be placed with different locations

meeting different percentages of Marshall density. While general specifications cannot state the maximum wind conditions during which construction might progress special conditions should be written into the contracts by local engineers familiar with the project site.

Another environmental factor that affects the rate of cooling of the bituminous mat in nearly the same manner as wind velocity is the ambient temperature. Figure 3-5 which has been reproduced from work by others[26] shows a resemblance to Figure 3-4. It should be observed that the rate

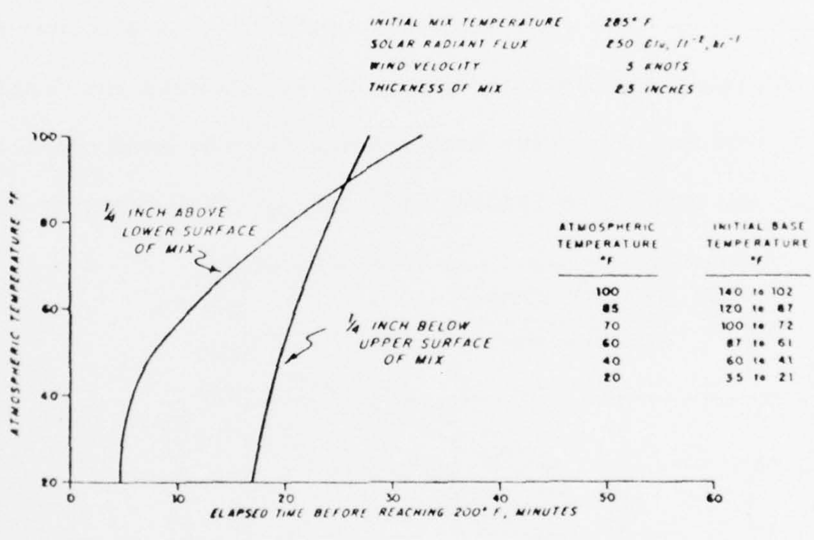

Fig. 3-5. Elapsed Time Before Reaching 200 F. vs. Atmospheric Temperature and Base Temperature, after Ref. 26.

of cooling near the top surface increases very rapidly with a temperature drop from 40°F (4.4°C) to 20°F (-6.7°C) while the rate is fairly constant at the bottom of the mat. Construction schedules can be planned to avoid laying pavements when the ambient temperature is below 40°F (4.4°C) and this is also the cessation requirement written into all FAA specifications

for asphaltic concrete pavement construction. At 40°F (4.4°C) the amount of time during which the contractor may effectively roll the pavement is of course quite limited.

While the emphasis has generally been placed on mixing and compaction temperatures the underlying variable is, strictly speaking, viscosity of the binder. Viscosity versus temperature relationships for various types and grades of asphalt have been the subject of extensive research and graphs are available showing the inverse dependence.[27] At high temperatures mixtures are seen to be less resistant to compaction than at lower temperatures when viscosities are higher. Figure 3-6 illustrates the densities attainable with various compaction temperatures for the same compactive effort. Studies at Ohio State University[27] and at the University of

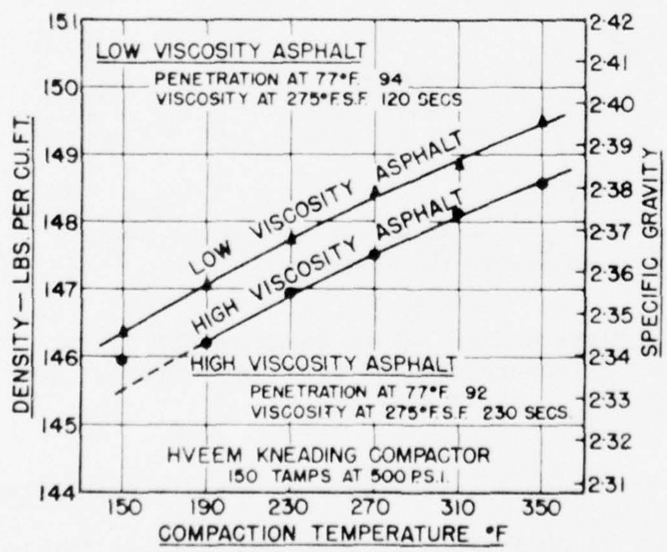

Fig. 3-6 Influence of Viscosity on Ease of Compaction, after Ref. 28.

Wisconsin[29] provide theoretical insight and experimental results by which the strength and mechanical properties of pavement mixtures

might be predicted for various viscosity and temperature conditions.

An example of the temperature distribution across the thickness of the mat moments after it is laid is shown in Figure 3-7. It is apparent that transfer of heat to the base is more rapid than to the air and that the rate of heat loss at mid-depth is least. The uneven rate of heat loss is even more pronounced in slabs thicker than for the 2.5 inches (6.4 cm) shown and while it is true that thick slabs will hold a high temperature long enough for rolling to be performed there are several problems in depthwise homogeneity.

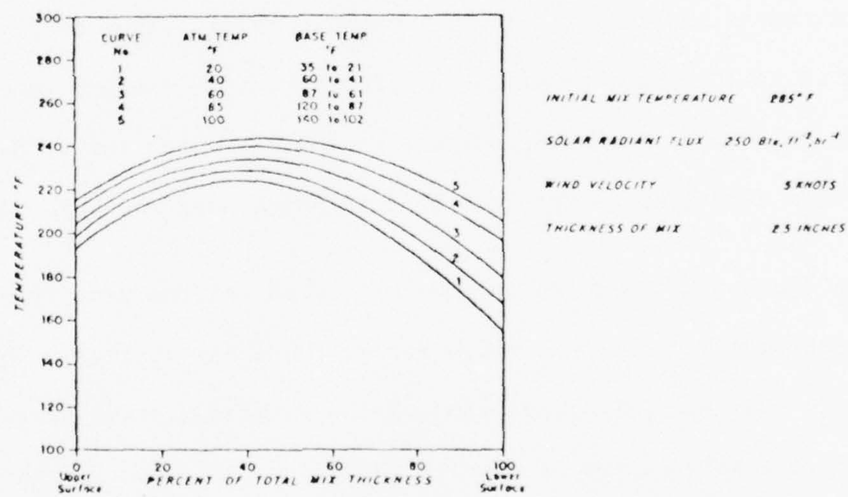

Fig. 3-7. Effect of Atmospheric and Base Temperatures on Temperature of Mix 15 Minutes After Placement of Mix, after Ref. 26.

The distribution of roller pressure through the mat thickness is of interest. In thin slabs the pressure distribution through the depth is generally taken to be nearly linear with a maximum near the top and a minimum value at the bottom. For thick slabs, however, the distribution is quite nonlinear and the bulb of pressure might never reach

the lower surface of the mat. Irrespective of the distribution it can be accurately stated that the compactive effort to which any slab is subjected cannot be constant through its depth especially when static rollers are employed.

Intensive experimental activity, some of which has been at Cornell University,[30] has revealed how bituminous pavement properties - specific gravity, stability, etc. - vary with compactive effort and temperature.[28] It might therefore be concluded that both the uneven distribution of temperature and the uneven application of compactive effort through the pavement thickness combine to produce an uneven distribution of physical properties in the finished product. The density, for instance, would be expected to be less at the lower surface of the mat where the temperature and compactive effort are least than at some point near the upper surface.

There is no doubt that when the pavement is cored and the density computed, the value obtained is only an average across the cross section. While it is not likely that specifications can ever be written to state maximum and minimum tolerable values of density through a cross section, the average density requirement should be maintained high enough to insure that minimally compacted locations in the cross section do not have too low a value. Many authorities, including the FAA, specify 98 percent of Marshall density as the minimum requirement for this average.

The laboratory Marshall stability at 96 percent of full compaction, for instance, is shown by Figure 3-8 to be as low as 50 percent of the value obtainable at 98 percent of full compaction.[28] Figure 3-9 also shows

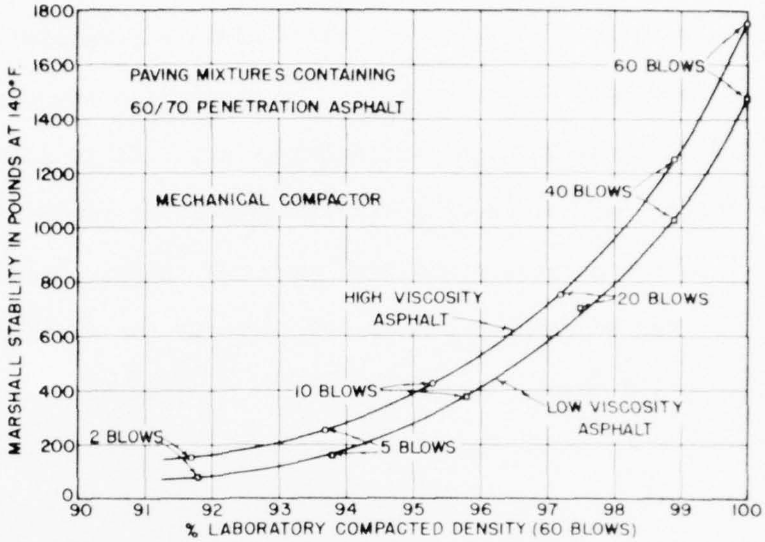

Figure 3-8. Marshall stability vs. percent laboratory compacted density for identical mixes containing low viscosity and high viscosity asphalt-cement, after Ref. 28.

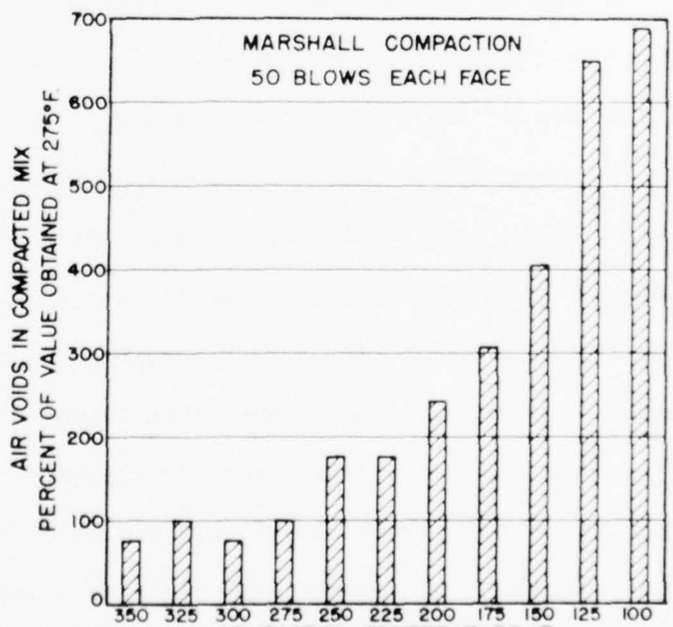

Figure 3-9 Influence of compaction temperature on percent air voids in an asphalt-concrete wearing course, after Ref. 28.

that an air void ratio of 4.0 percent for a mixture compacted at 275°F (135°C) would have been 12.0 percent if the compaction temperature had been 175°F (79°C) with the same compactive effort. It is understandable that, other factors aside, deterioration of asphaltic concrete pavements would begin from the underside and work upwards. Also, a reduction requiring less than 98 percent of Marshall density for average cross sectional compaction means a reduction in the density of those areas that are already well below the 98 percent value. Performance studies at Washington State University with test tracks reveal that under service conditions cracks first develop on the underside of asphaltic concrete courses.[31]

Current practice on airport projects is to set a maximum lift thickness for asphaltic concrete pavements at 3.0 inches (7.6 cm). While it is true that a lift of this dimension is not impossible to compact to the required density, the imposition of a requirement that this thickness be done in two lifts would present some advantages. Firstly, the temperature distribution through the cross section would be fairly even for each 1.5 inch (3.8 cm) lift. Secondly, for any roller, the compressive stresses reaching the bottom of a thin lift are higher than those at the bottom of a thicker lift. A roller that is too light to compact a 3.0 inch (7.6 cm) lift adequately might therefore be very effective on two 1.5 inch (3.8 cm) ones. Thirdly, the lower lift serves as a seal for the upper one. Fourthly, more control of elevations and roughness becomes possible. It is true that a two lift operation would require more construction time but the advantages derived from a tighter pavement would be cost effective.

Experience has shown that field compaction of bituminous mixes is not easily accomplished within the first eight minutes of laydown. During this period the incidence of shoving of the mixture, cracking in the mixture and pickup by the roller drums or tires is at its greatest. It must be noted that the higher the temperature of the mixture the more liquid the matrix becomes making compaction impossible. Thus under constant roller pressure, compaction is possible within a band of the temperature scale impossible at higher temperatures as well as at lower temperatures. Here the factor dictating temperature of the laid material is time and for most rolling operations the optimum period for effective compaction is between eight and sixteen minutes after laydown. Of course this time band can be widened somewhat if the load applied to the pavement by the roller is lessened at the higher temperatures and increased as the pavement gets cooler. This is a common practice when pneumatic rollers with variable tire pressures are used.

A model utilizing heat transfer theory has been developed by the University of Illinois and the State of Illinois Transportation Department[32] to predict cooling time (time lapse for temperature to fall from mixing temperatures to 175°F, 80°C) for the various design and environmental conditions associated with bituminous pavement construction. Extensive material testing has to be done to determine the values of some of the input variables. However, when these are known the model will provide a figure for cooling time that should enable the contractor to estimate the number and closeness of the units for his paving train.

All other factors being equal, the amount of drawbar pull exerted by a small diameter roller is greater than that exerted by a large diameter one.

The extra work done derives from displacing and pushing the laid material. The amount of contact on the pavement by a small diameter roller is less than from a large one and this induces higher compaction stresses causing greater vertical displacement of the contacted area. As the roller moves it shoves the pavement before it and could cause decompression of areas already compacted in earlier passes. Comparative figures[33] of drawbar pull on various materials have shown that the drawbar pull on a 46 inch (116.8 cm) diameter roller can be as much as 60 percent greater than for a 72 inch (182.9 cm) roller. For example, on one bituminous concrete pavement when steel tired rollers were used, the drawbar pull for 46" (116.8 cm) diameter was nearly 900 pounds (4.00 kN) versus 560 pounds (2.50 kN) for a 72" (182.9 cm) diameter roller.

Compaction may aptly be considered as the result of a force which brings the aggregate of the pavement mixture closer together. In order for this to occur there has to be a vertical displacement of the compacted material. The amount of compaction - displacement - varies directly with the magnitude of the force and inversely with the stiffness of the material. When a compactive force is applied it is reacted by the product of the stiffness (force per unit displacement) and displacement of each layer in its path. The freshly laid mixture is in a plastic condition (no rebound occurs after removal of a force) and may be compacted only if a reaction can be provided by the underlying layers - base, subbase and subgrade. If these layers cannot provide the reaction, for instance if they undergo plastic yield under the roller, compaction of the bituminous mat is not possible. Also, if the support is spongy (low elastic modulus) elastic displacement will

be large and as the roller moves rebound of the pavement behind the wheel will occur. Fracture under excessive horizontal strains also occurs reversing the compactive effort. The deflection of underlying layers has been shown by New York State Department of Highway studies to be a major factor influencing pavement density.[23] A strong, unyielding, well compacted base must exist; otherwise, the mat cannot be compacted to the required density.

Mixes of very high stability are achieved when the aggregates are composed of crushed stone with fractured faces as opposed to mixes with rounded gravel of smooth texture. Indeed, the mix can be so stable that very little compaction is possible with any given roller. Conversely, the mix might have such a low stability that it cannot bear the pressures from the roller without excessive deformation. For any particular stability there is therefore an optimum roller wheel load that will effect the desired degree of compaction. On airport bituminous pavement projects Marshall stabilities of above 2,500 lbs or 11.12 kN (1,800 lbs or 8.00 kN min. required by FAA) are common. In one instance 3,800 lbs (16.80 kN) was recorded and considerable difficulty was experienced in achieving compaction to 98 percent of Marshall density even after vibratory rollers were brought in to aid in the compaction effort.

Studies on compactibility of high stability pavement mixtures have shown that compaction is improved by lowering the Marshall stability or increasing the Marshall flow value.[14] This is equivalent to lowering the bearing capacity to some limiting stress which would not cause failure under compaction. The State of Michingan Highway Department also conducted

investigations which showed that there is little or no additional compaction from intermediate pneumatic tire rolling on mixtures with very high stability.[34] Mixes with very low stability could not be compacted to high density because the roller tended to sink into the overstressed pavement material causing it to shear and shove laterally with development of cracks.

It has been found that the roller weight and configuration, tire pressure and number of passes necessary to obtain maximum density vary from project to project. Such factors as aggregate gradation and texture, mix composition and stability, viscosity, laydown temperature, wind velocity and ambient temperature influence the optimum compaction procedure. While specifications should not be written to restrict the contractor to any particular type, weight and number of passes of rollers certain procedures have been found more effective than others in attaining the specified degree of pavement compaction. Work done in Canada to compare the effectiveness of various types of roller weights, types and configuration at a fixed number of passes revealed that a 10 ton (89 kN) steel tandem roller used for breakdown with from 5 to 7 passes, followed by an intermediate roller weighing 30 tons (267 kN) with pneumatic tires at 60 psi (414 kPa) and 13 passes, followed by an 8 ton (71 kN) steel tandem finishing roller with 3 passes gave the highest degree of compaction even with the harshest mixes. The degree of compaction achievable consistent with good riding qualities of the pavement was found to be a function of void content, Marshall stability and flow as mentioned in an earlier paragraph of this report. While studies[35] such as those made abroad on rolling

techniques are useful to acquaint contractors with the state of the art the requirement of a test section is sometimes worthwhile to provide a means by which the types of roller, number of passes and other factors can be determined to achieve 98 percent of Marshall compaction for each project.

In practice, smooth steel tired rollers, rubber tired pneumatic rollers and vibratory rollers are the most common types of field compaction equipment. In contrast to the two other types which compact the pavement by static pressures the vibratory rollers compact by setting up a rapid succession of impacts against the pavement surface thereby creating pressure waves. These waves put the mixture particles in motion, cause the fines to fill the gaps between the coarse aggregates, exhaust the air voids and create a near uniform densification in depth of the paving material.

The ability to put the aggregates in motion makes the vibratory roller successful in bypassing the high friction values associated with high stability mixes. The mechanics by which the material is compacted also enable lifts of up to 8 inches (20.0 cm) thick to be densified in contrast to the usual 3 inches to 3.5 inches (7.6 to 8.9 cm) barely possible with static rollers. Somewhat lower than normal laydown temperatures have also been used because of the high efficiency of this type of roller.

Vibratory compaction of bituminous paving material had been practiced in Germany and Sweden before becoming popular in the United States.

But while specified minimum densities for airport pavements have in general been achieved quicker and at less cost than by any other means some observers believe that the enthusiasm should be cautious because these rollers are not suited for all types of compaction problems. Specifically, on asphaltic concrete pavements,

a) over compaction is very likely,

b) decompaction of already rolled underlying layers is possible, and

c) Liquefaction of thixotropic subgrade material is also another possibility.

A recent development in the construction of bituminous pavements has been the dryer drum process. In this process, aggregates enter the heater end of a cylindrical drum and are blended by lifting paddles within, heated and sprayed with hot bitumen. Some advantages derived by using this process have been that the asphalt does not oxidize, age and harden as much as in the conventional pugmill process, less air pollutants are produced, lower mixing temperatures are effective and the mixture is, reportedly, easy to compact to the required minimum density due to its higher than normal moisture content which acts as a lubricant.[38]

IV. QUALITY ASSURANCE

Many occasions have been encountered in which pavements were constructed to specifications and, because of the lack of accurate testing facilities, were believed to be substandard. Sometimes, too, laboratory facilities are located so far from the work site that when test results are learned it is invariably too late for effective remedial actions. Precise and immediate quality control is an essential part of any production process and, especially where large sums of money, loss of property and public safety are involved, should always be delineated in the contract specifications and enforced.

Because of variability in the competence of operators and the intrinsic variability of the testing instruments themselves it is impossible to state with any certainty that the density of one sample represents the density of the compacted pavement. While 98 percent of Marshall density is regarded as a reasonable minimum degree of compaction to expect, accepting or rejecting a part of the pavement because of the result of one sample is an incorrect approach. What is generally specified by some agencies, including the Naval Facilities Engineering Command, is that the results of four samples be averaged and that this average should not fall below some minimum value. The maximum number of samples falling below the required minimum and their maximum deviation are also necessary limits so that while making allowances for experimental error they still demand a certain amount of care on the part of the testing personnel.

A survey of field records of most airport bituminous pavements which failed to meet Marshall compaction requirements suggests that these requirements could have been met on some of them if individual core densities were averaged. Consistent low readings in specific areas of the mat would naturally indicate that those areas were not sufficiently compacted but when low and high readings for a day's paving are evenly dispersed throughout the area of the mat the inference could be that the mat was adequately compacted and that the variations were the result of testing errors only.

It would also be possible to so select areas for density determinations that the pavement density, as averaged, would meet the compaction minimum although large areas had been insufficiently compacted. To avoid this the lot which constitutes the unit of four samples ought not to be averaged with other lots and the distance between samples in a lot ought not to exceed say 15 feet. The location of the lot on the pavement should be determined by random selection as outlined by a research report prepared by the Corps of Engineers.[36]

The preparation of Marshall cylinders from the pugmill is in many cases done by drawing four samples and using their average density. The Corps of Engineers suggest that the selection of samples be done on a random basis and have also published a list of random numbers that would form the basis for the selection. While random selection precludes bias, if the engineer has reason to think that the quality of the mixture is questionable he usually takes samples in any manner he sees fit.

The samples of bituminous mixture that are to be compacted and used as the standard of density are on many projects taken from the truck, transported to the laboratory, reheated, compacted and weighed. Since the compacted specimens are meant to represent a base from which to measure field compaction they should be as akin as possible to the field samples. Some of the areas where similarity is essential are:

a) composition

b) compaction temperature

c) compaction method

d) density evaluation

a) It has not been shown by reports from projects that samples obtained from the pugmill, or from trucks or behind the pavers are different from each other in composition. However, it appears that more certainty concerning similarity of composition with or without segregation would be possible if those samples were taken from behind the paver.

b) The temperature at which rolling on the pavement takes place usually begins at 275°F (135°C) and ends at 175°F (80°C). Mixture samples for Marshall compaction are however compacted at some constant temperature determined by the viscosity of the asphalt. While some incongruity exists, the general preference among technologists is that the specimen compacting temperature should be the one at which the viscosity is 280 $\pm$ 30 centistokes. Hard and soft asphalts would have the same compactibility even though one would need a higher temperature for compaction

than the other. Setting one compacting temperature for all types of asphalts is an incorrect procedure.

Reports have been seen in which technicians erroneously compacted bituminous samples at temperatures approaching mixing temperatures. (The Asphalt Institute recommends the use of compacting temperatures when viscosity is at 280 $\pm$ 30 centistokes and mixing temperatures when viscosity is at 170 $\pm$ 20 centistokes.)[4] The result was that the pavements appeared to have been undercompacted because of the higher densities obtained for the Marshall samples at the elevated temperatures. When this procedure was corrected the degree of mat compaction was computed to be 98 percent of Marshall density or greater.

Another practice observed on many airport projects is that samples of the mixture are reheated prior to compaction. This practice is improper and should never be permitted. The samples of hot-mix asphalt concrete cool to ambient temperature within 30 minutes and therefore compaction has to be carried out within the first few minutes after mixing or laydown. Attempts were made by some technicians to raise the temperature of cold samples to the specified compacting temperature but when this temperature was reached the asphalt invariably had a lower viscosity than originally intended because of some oxidation and loss of volatiles. Compaction of these samples is more difficult and densities obtained lower so that pavement cores in comparison seem to have a higher degree of Marshall compaction than would have been otherwise obtained.

c) The degree of densification that particulate materials can experience is not only determined by the intensity of compactive effort but by the manner in which the effort is applied. The Marshall specimens are compacted by impact from a 10 lb. (4.54 kg) hammer dropping a distance of 18 inches (45.72 cm) 50 or 75 times while the mat is compacted by static or vibratory rollers. Notwithstanding these differences in manner of compaction, the laboratory specimens provide a useful "yardstick" and the practice of sometimes compacting specimens against the pavements, according to some reports, rather than against wooden plates as provided for in the ASTM recommended procedures[9] will lead to inconsistent Marshall densities that cannot be used for purposes of comparison.

d) In order to compare the density of the compacted pavement with that of the Marshall specimen the methods by which these are evaluated should be similar. On most of the projects surveyed this is done because cores are taken from the pavement for evaluating density. In recent years, however, the use of nuclear densometers has been increasing and there have been several examples in which, despite some advantages that the densometers offer, site engineers have had to revert to the taking of cores to evaluate density. Nuclear densometry has the advantage of being a nondestructive testing method. Densities of pavement masses can be obtained very rapidly and

therefore many more readings can be taken than are possible with other methods. But reading instabilities have been experienced on many airport paving projects while in others low Marshall densities were indicated and found to be erroneous only after cores were taken. The practice has been to use nuclear densometers only as quick checks and to require the taking of cores at intervals to insure that densometer readings are not in error. It should also be noted that, aside from certain intrinsic errors, the reliability of nuclear gages varies according to type and manufacture and when a finished pavement is to be accepted or rejected on the basis of degree of compaction a more direct test might be advisable.

A method that helps to insure that the rolling procedure will be adequate to achieve the minimum pavement compaction and quality is to require the laying of a test stip. This practice is in use by the Federal Highway Administration, the Department of Defense and some other agencies. The intention here is to afford the contractor a means whereby he may determine the best roller weight and rolling pattern prior to commencing paving operations on the main project. While such an effort may be useful, and indeed necessary on some projects, some engineers believe that the benefits derived from constructing a test strip are perhaps dubious and may not repay the cost of its construction. Some of the observations made are that:

a) The stiffness of the underlying layers will affect the degree of compaction attainable for the bituminous mat in the test strip. Variations in stiffnesses - support reactions - over the project site require different roller weights or patterns to attain the same degree of pavement compaction, other conditions being constant. These differences will be minimized if the test strip is located in the area to be paved and, preferably, where intensity of traffic is expected to be light.

b) Difference in ambient temperature, base temperature, wind velocity, base moisture content, etc. between what were experienced in the test strip and those on the main project make changes in procedure necessary to attain an equivalent degree of compaction.

c) Successful paving procedure on the test strip does not obviate the need to make the usual number of tests to insure that adequate compaction has been achieved on the airport pavement. Some State Highway Departments require that contractors make only a certain number of passes with a roller of a certain weight as determined from the strip. Contractors accustomed to this arrangement would expect that an airport paving project follows the same procedure and a disclaimer to the contrary would have to be written into the job specifications.

d) The requirement that a test strip must be laid will increase the bid price for the contract. On smaller jobs, it is believed that the additional cost could amount to a substantial percentage of the cost of the project itself. A dollar limit might be used to avoid too high a percentage but it must be understood that the same reasons that would make a test strip necessary for a large project are the same ones that apply for a smaller one.

e) If all the factors that might affect compaction are understood and effective remedial actions based on past experience known, then the test strip serves only to increase the skill of the equipment operators - a function for the contractor and not for the airport sponsor.

f) A preaward conference provides a forum in which customary roller weights, passes and procedures based on experience on similar paving projects could be disclosed. These items need not be learned on a test strip after award of the contract.

A practice which is common in airport paving projects is to require that contractors be paid a portion of the contract price according to the degree of pavement compaction he was able to accomplish. At 98 percent of Marshall density he would gain the full price, at 97 percent he would gain a lesser amount and so on. This arrangement is intended to insure that the contractor has an incentive to attain the minimum pavement density requirement. While there have been occasions where this practice

has been used with some success there are several considerations that must be evaluated:

a) A much greater degree of effort and control is required to get from 97 percent of Marshall density to 98 percent than is required to get from 96 percent to 97 percent. If the sliding scale is not well structured it could prove to be to the contractor's advantage to compact the pavement to only 97 percent of Marshall density even with the reduced fee he would receive.

b) The degree of compaction of the pavement from one point to the next is shown by experience to vary. The application of a sliding scale based on such a variable parameter and that would be fair to all sides would of necessity be quite complex. It is also possible that one random selection of cores could show that the compaction meets the minimum while another shows that it does not. In order to avoid dispute some system would have to be devised to base payment on the average density of several agreed on points over a specified length of pavement lane.

c) After the contractor is penalized for having constructed a pavement compacted to 97 percent of Marshall density (however determined) the sponsor still ends up with substandard pavement. Remedial work such as an extra lift, ripping out and recycling could reasonably upgrade it and might be paid

for out of the difference between original contract price and what the contractor had been paid if the latter were made low enough.

Alert construction supervision has on many airport projects been able to avert poor compaction of bituminous mixes by immediate adjustments to parameters such as mix design, laydown temperature, roller type etc. when the need arose. The spiralling cost of materials and labor, the need to conserve natural resources and expensive remedial work with delays are only a few reasons why knowledgeable and effective guidance must be present on the site. Investigation also reveals that many FAA engineers believe that increased participation by the Federal Government in financing paving projects should be matched by greater efforts on its part to obtain a quality product and that this could best be accomplished by requiring the presence of its representative during construction operations.

V. CASE STUDIES

The cases outlined on the following pages are examples showing steps by which required Marshall density requirement was obtained at certain airport bituminous paving projects after initial failure to achieve it was experienced. In many instances the same results could have been attained by varying other parameters. It should be observed, also, that while general principles can be established in paving technology each situation presents unique circumstances and, therefore, the solutions employed are to be considered as guidelines only.

PROJECT NO. 7-29-0068-01

This contract required the construction of flexible pavement for a complete runway, taxiway and apron at a new airport. A 2 inch (5.08 cm) thick asphalt concrete course was to be laid over a 4 inch (10.16 cm) aggregate base course supported by an FAA type F-1 subgrade.[37] The airport serves as a general aviation facility.

The asphaltic concrete was designed with a Marshall stability of 1,330 lbs (5.91 kN) at a flow of 14.6 (The Marshall stability required by the FAA for pavements on this type of airport is 1,000 lbs. or 4.44 kN.) All of the aggregates consisted of river material and asphalt cement had a penetration of 85/100.

This mixture should have been workable enough for adequate compaction to be achieved with modest compactive effort. However, 98 percent Marshall was not consistently achieved and core samples indicated densities varying from 87 percent to 99 percent of Marshall density. While information on many of the variables connected with compactibility are missing from the field records, it is reported that there was inadequate project control on the site and also that the testing laboratory was 250 miles (400 km) from the construction site. Therefore, when laboratory reports were received concerning low density of cores, for example, it was too late to make any adjustments in laydown temperature, number of roller passes, etc.

The project was started in 1974 and after only two years its performance has been rated as poor to fair.

PROJECT NO. 7-37-0010-01

This project consisted of laying a 2.0 inch (5.08 cm) thick asphaltic concrete course on an 8.0 inch (20.32 cm) thick base for an airport taxiway and apron. The airport is a general aviation facility serving light aircraft.

The aggregates forming the paving mixture were of good quality, had many fractured faces and conformed generally to an FAA Type B gradation. The design Marshall stability was just over 3,600 lbs. (16.0 kN). The FAA requires a minimum of 1,000 lbs. (4.45 kN) on general aviation airports and 1,800 lbs. (8.5 kN) on air carrier airports.

Attempts to compact the mat to 98 percent of Marshall density based on a 75 blow effort failed and pavement densities ranged from 94 percent to 97.5 percent. A test section was then constructed to determine the best roller weight and rolling pattern that would produce the minimum compaction required but this was also unsuccessful. The pavement densities however were over 98 percent of Marshall when compared with a laboratory compaction effort of 50 blows.

While several other factors, not in the project records, could have hindered the achievement of adequate compaction, the very high stability of the mix was doubtless a major factor. High stability bituminous mixes are known not to yield enough under the weight of static rollers to be adequately compressed. Greater ease in compacting the mat would have been experienced if the mix had been designed with a stability closer to the minimum requirement.

The condition of the pavement now three years old and serving light aircraft is considered to be good.

PROJECT NO. 7-37-0053-01

The job at this general aviation airport was to lay a 2 inch (5.08 cm) thick asphaltic concrete course on top of an 8 inch (20.32 cm) thick crushed aggregate base course for a taxiway and apron. The subgrade was type E-5 based on FAA classification.[37]

Pavement cores compared with 50 blow Marshall specimens showed a range of 97.4 percent to 102.2 percent of Marshall density. The mixture had been designed for a stability of about 1,900 lbs. (8145 kN) nearly twice the minimum FAA requirement for this type of airport.

Although the field records do not give details of all the conditions encountered at the site, it is seen that the Marshall stability was low enough to give a relatively tender mix for the roller type employed and that the field specimens were being compared to laboratory samples compacted to only 50 blows. These two factors would contribute to the high percentages of Marshall densities that were obtained.

PROJECT NO. 7-39-0048-01

The requirement at this air carrier airport was to construct a new flexible pavement consisting of 4 inches (10.16 cm) asphaltic concrete on 12 inches (30.48 cm) crushed aggregate base course over a subgrade of clay compacted to 95 percent of maximum density at optimum moisture content. Work began in the summer of 1975 and was completed in 6 weeks.

The bituminous mix consisting of a blend of both crushed and natural aggregate sizes had a Marshall stability of 1,800 lbs. (8.0 kN), the minimum allowed by FAA for pavements in this type of airport, and a corresponding flow value of 10.

Because the subgrade consisted of clay that was inadequately compacted, the contractor had difficulty in compacting to 100 percent density the 3-4 inch (10.16 cm) lifts of crushed aggregates that formed the base course. Difficulty was also encountered in attaining the 98 percent minimum of Marshall density for the surface course because he was using rollers suitable only for roadway construction. After a vibratory roller was hired, later core samples indicated pavement densities varying between 96 percent and 104 percent of Marshall density.

PROJECT NO. 8-04-0045-05

The project consisted of a 3 inch to 5 inch (7.6 cm to 12.7 cm) asphaltic concrete (AC) overlay on an existing AC runway, taxiway and apron pavement. The airport serves as an air carrier facility and accommodates close to 17,000 departures per year.

The AC mix was designed with a Marshall stability of 2,100 lbs. (9.33 kN) at a flow value equal to 9 and asphalt content amounting to 6.0 percent by weight. The laydown temperature was generally 250°F (121 °C) but fell to low values of 225°F (107.2°C) in some areas although the design mix had called for 275°F (135°C). Variations in the viscosity of asphalt supplied to the contractor were also experienced. The field laboratory personnel sometimes compacted specimens at higher temperatures than the design temperature and some densities were recorded as low as 91.3 percent of Marshall density.

Better densities were obtained by changing the asphalt supplier, establishing careful controls on the laydown temperature and reducing the time between laydown and the initiation of rolling. In addition, the low density problems which were caused by poor testing procedures were corrected by insisting that samples be compacted at the design temperature and adhering strictly to ASTM testing procedures.

PROJECT NO. 8-06-0170-02

The contract at this air carrier airport required the construction of an asphaltic concrete overlay on an existing Portland cement concrete pavement and, also, a full depth flexible pavement for a taxiway and apron. The overlay portion of the project was to serve light aircraft while the full depth pavement was to serve aircrafts with weights exceeding 30,000 lbs. (13.61 Mg).

The design mix for the asphaltic concrete pavements made use of some natural sand but coarse aggregates were manufactured. Marshall stability of the mixture was measured at 2,830 lbs. (12.58 kN) while flow was 11. For field compaction, vibratory rollers were employed — 31 ton (28.12 Mg) double drum for breakdown and intermediate rolling and a 21 ton (19.05 Mg) for finishing.

The degree of pavement compaction was measured by nuclear gages which were later discovered to be indicating densities of over 2.0 percent less than what core samples indicated. These gages also indicated a wide variation in pavement densities ranging from 93.0 percent to 100 percent of Marshall density. It was also discovered during construction that some loads of the mixture when delivered to the site had poorly graded aggregates and lower bitumen content than required by design. Conditions during construction were windy (13.0 knots) but ambient temperature was mild (50°F or 10°C).

Remedial work involved applying a rejuvenating agent to the pavement and laying an additional inch of asphalt concrete.

PROJECT NO. 8-16-0003-16

This project required the construction of an asphaltic concrete overlay on an existing runway. The work started in 1975 and a determination concerning what remedial work should be carried out has still to be made. All the important factors working against the attainment of adequate compaction were present on this job.

The design mix for the asphalt concrete had a stability of 3,580 lbs. (15.9 kN) at a flow of 13. The aggregates had high porosity and were improperly graded with insufficient fines in the minus #200 sieve size and were formed entirely by crushing.

Construction of the mat was repeatedly delayed by adverse weather conditions such as high winds, varying ambient temperatures and precipitation. When the mixture was finally laid both static and vibratory rollers were used to compress it. A great amount of difficulty was experienced in trying to get pavement compaction in excess of 96 percent of Marshall density. In general, nuclear densometers gave such erratic readings that they could not be relied on and densities had to be determined exclusively from core samples. Minor variations in gradation, oil content, laydown temperature and rolling pattern were not effective in raising the degree of compaction to 98 percent of Marshall density.

The engineer's report on this project states the position that 96 percent compaction is acceptable if all the other factors involved with pavement construction are met. It does not state that air void ratio in place is nearly 8.0 percent and that the resistance to compaction was largely due to the excessive stability of the mix.

PROJECT NO. 8-17-0022-06

This project required the construction of a full depth flexible pavement for runway shoulder and fillet and, also, overlay of an existing runway at a hub international airport. The work on this contract lasted for three months and was completed in 1975.

The design mix had a maximum Marshall stability of 2,300 lbs. (10.23 kN) at a flow 12. Compaction which was accomplished within 15 to 20 minutes of laydown was carried out by both vibratory rollers weighing from 12 to 20 tons (10.89 to 18.14 Mg) and static rollers weighing 18 tons (16.33 Mg).

Ambient temperature during construction was about 50°F (10°C) and temperatures of the pavement at the completion of rolling varied from 220°F to 230°F (104°C to 110°C). The degree of pavement compaction was determined from core samples to be from 96 to 99 percent of Marshall density with an average of 98 percent.

No special problems were experienced in obtaining 98 percent minimum of Marshall density and the low readings could be considered as due to construction, material and testing variability. The condition of the pavement is up to this date still excellent.

VI. SUMMARY AND CONCLUSION

While it is true that a finished pavement must be judged on more than one single standard for quality, for a bituminous pavement, at least, the degree of compaction is perhaps the most important factor affecting its eventual ability to perform. Conclusive laboratory studies have shown how the strength of such a pavement increases with compactive effort and other studies have indicated the loss of durability that arises from excessive air voids. Spiralling construction costs and increasing scarcity of material resources demand that pavement life be not jeopardized by inadequate compaction.

The vast majority of engineers interviewed and involved in the construction of bituminous pavements believe that while the 98 percent minimum of Marshall density is a practical, worthwhile and achievable requirement an accurate determination of the extent of pavement compaction cannot be made from the results of one sample. Variability in the accuracy of testing equipment, skill of operators and material quality, etc. demands that the degree of pavement compaction achieved be based on the average density of several samples.

At least fourteen parameters directly affect pavement compactibility and, when their limits are not recognized, the most frantic efforts to compact the pavement are futile. No amount of rolling can compact an incompactible pavement. In most cases where failure to reach the minimum compaction has been investigated the causes were discovered to be due to mixtures with excessively high Marshall stability, mixture was not laid at a high enough temperature to neutralize too rapid coding, rollers were

too light or of wrong type for the particular mixture stability, supporting layers were too weak or testing equipment and technicans were at fault. In some of these cases rolling time was extended causing job delay and additional expense but when it was realized that this led to virtually no density increase changes were made in mix design, construction equipment, subgrade strength or testing procedures which later proved to be successful.

VII. RECOMMENDATIONS

Based on the information gathered from survey, interviews and study of the state-of-the-art the following recommendations to facilitate adequate bituminous pavement compaction are made:

1. Require 98 percent of Marshall density as the minimum average degree of compaction for asphaltic concrete pavements.

2. Permit the determination of density for an area of pavement to be based on the average of four closely spaced samples rather than on one and that no more than two of these four samples may be less than 96 percent of Marshall density.

3. Require that, in the design of bituminous mixes, the peak Marshall stability be no greater than 2,500 lb (11.0 kN).

4. Reduce the required minimum percentage by weight of coarse aggregates with two fractured faces from 75 to 50 and those with one or more fractured faces from 90 to 75.

5. Require that nuclear density gages be used only in conjunction with core samples as a means of obtaining pavement densities.

6. Require the presence of a laboratory on the construction site (or at the plant) with all the equipment necessary to insure quality control.

7. Require that resident engineers for duty on the site of all federally aided paving projects be certified by FAA District

Offices before the beginning of construction in order to insure compliance with engineering, construction and testing practices.

8. Establish a requirement that the maximum pavement thickness that can be rolled in one lift is 3 inches.

9. Require that paving contracts state that permission to follow procedures resulting in successful compaction on a test strip, where employed, is not a waiver of the requirement to achieve adequate compaction on the project pavement.

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